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Topics

1. **Cooper-pair insulators**
2. **Many-body localization of bosonic systems**
3. **Spectral properties and the pseudogap state**
4. **Strongly disordered nanowires and quantum phase slips**
5. **High frequency properties of strongly disordered superconductors**
6. **Novel hybrid and gate-tunable systems**

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Organizing Committee

- **Vincent BOUCHIAT**, Institut NÉEL, CNRS-Grenoble
- **Claude CHAPELIER**, CEA-INAC, Grenoble
- **Eduard DRIESSEN**, CEA-INAC, Grenoble
- **Julia MEYER**, UJF & CEA-INAC, Grenoble
- **Yuli NAZAROV**, TU Delft & Nanoscience Foundation
- **Benjamin SACÉPÉ**, Institut NÉEL, CNRS-Grenoble

Scope

Strongly disordered superconductors are attracting much interest due to the intriguing new states of matter that exist in the vicinity of the superconductor-insulator transition (SIT) and due to their potential applications in THz detection of astronomical signals and in quantum information devices.

In the last few years, the number of experimental techniques used to investigate strongly disordered superconductors has significantly increased. Hand in hand with new theoretical developments, they provide new insights into the nature of superconductivity close to the SIT, and into the phenomena that accompany it.

This workshop strives at bringing together the world leading scientists in this field, both experimental and theoretical, to share their latest understanding of the underlying physics, discuss newly available techniques, and define future directions for the research on strongly disordered superconductors.

Site

The workshop will take place during the week 9-14 February 2014 in the beautiful ski resort of Villard-de-Lans on the Vercors Plateau, 25 km south of Grenoble, at:

**** BEST WESTERN GRAND HÔTEL DE PARIS
124, place Pierre-Chabert
38250 Villard-de-Lans
Ph: 04 76 95 10 06

Located in a 3-hectare private park in the centre of Villard-de-Lans, the Grand Hôtel offers access to all the facilities of a touristic town: ice rink, water park, casino, bowling alley, shuttle service to the ski slopes...

Excursion to a mountain refuge

Wednesday February 12th (18:30)

We are organising a special mountain evening on Wednesday night. This will include a 45-60 minutes walk on snow shoes, after which we will have dinner in a mountain shelter. The return walk will be a torch-lit descent, and will take about 20 minutes.

Snow shoes will be provided, but you will need to bring warm clothes, gloves and walking boots (no snow boots). There will be no extra costs attached to participation.

After introduction and delivery of equipment by qualified instructors, our partner ”Vercors Adventure”, you will go for a little night walk at your own pace. A good way to get some fresh air after a day’s work! Along the way you will meet with the natural surroundings in which you operate. This efforts will lead you in a typical and cozy place where Eleanor & David Pasqualon will be pleased to welcome you.

Typical alpine dinner in a mountain shelter

Menu ”Raclette”: The name ”raclette” (pronounced ruck-lett in English or rah-klett in its native French) refers to a meal and to a type of cheese with the same name.

The traditional dish can be described as melted cheese eaten with boiled (or roasted) potatoes accompanied by sliced meat.

Equipment

Gear provided: snowshoes; snow sticks; headlamp / torch. Possibility to rent some hiking boots if needed.

Your own personal equipment: hiking boots or snow boots; warm and waterproof clothing; cap; gloves.

Transfers from / to the hotel by bus (approx. 20 minutes).

Conference program

Sunday 9 February

18:00	**Arrival of participants and dinner**	

Monday 10 February

8:30	**Dan Shahar** *Duality near the superconductor-insulator transition*	0 h 45
9:15	**Jim Valles** *Amorphous nano-honeycomb film investigations of disorder effects on the SIT and transport deep in the Cooper pair insulator phase*	0 h 45
10:00	**Mikhail Feigel'man** *Superconductor-metal transitions in 2D*	0 h 45
10:45	**Coffee break**	0 h 30
11:15	**Konstantin Efetov** *Cascade of phase transitions near quantum critical point*	0 h 45
12:00	**Julius Ranninger** *Insulator-superconductor phase transition in crystalline metastable materials*	0 h 30
12:30	**Lunch and free time**	4 h 00
16:30	**Coffee break**	0 h 30
17:00	**Peter Armitage** *Microwave spectroscopy evidence of superconducting pairing in the magnetic-field-induced metallic state of InO_x films at zero temperature*	0 h 45
17:45	**Aviad Frydman** *Collective modes in disordered superconductors*	0 h 45
18:30	**Alessandro Monfardini** *Superconducting micro-resonators for radiation detection*	0 h 45
19:30	**Dinner**	

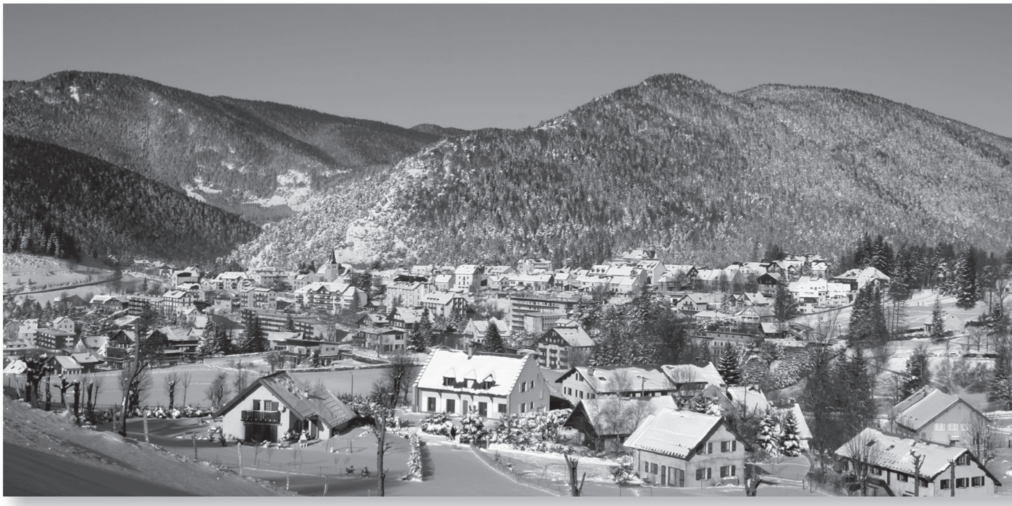
Tuesday 11 February

8:30	**Pratap Raychaudhuri** *Emergence of nanoscale inhomogeneity in the superconducting state of a homogeneously disordered s-wave superconductor*	0 h 45
9:15	**Hermann Suderow** *Disorder and Coulomb interactions in quasi two dimensional superconductors*	0 h 45
10:00	**Claude Chapelier** *Tunneling spectroscopy of localized preformed Cooper pairs in highly disordered superconducting Indium oxide films*	0 h 30
10:30	**Coffee break**	0 h 30
11:00	**Tristan Cren** *Spectroscopic properties of ultrathin NbN films close to the superconductor–insulator transition*	0 h 45
11:45	**Nandini Trivedi** *Emergent granularity, robust Cooper pairs, and spectroscopies across the superconductor-insulator transition*	0 h 45
12:30	**Lunch and free time**	4 h 00
16:30	**Coffee break**	0 h 30
17:00	**Claudio Castellani** *Current patterns and optical conductivity in disordered superconductors*	0 h 45
17:45	**Eduard Driessen** *Microwave electrodynamics and local tunnelling spectroscopy of strongly disordered superconducting thin films*	0 h 45
18:30	**Mikhail Skvortsov** *Electromagnetic response of strongly disordered superconducting films*	0 h 45
19:30	**Dinner**	1 h 30
21:00	**Poster Session**	2 h 00

Wednesday 12 February		
8:30	**Alexey Bezryadin** *Macroscopic tunneling of double phase slips in superconducting nanostructures*	0 h 45
9:15	**Andrey Rogachev** *Superconductor-Insulator Transition in Long Nanowires*	0 h 45
10:00	**Konstantin Arutyunov** *Insulating state of a quasi-1D superconductor stimulated by quantum phase slippage*	0 h 45
10:45	**Coffee break**	0 h 30
11:15	**Lev Ioffe** *Quantum phase transitions in Josephson junction chains and ladders*	0 h 45
12:00	**Karen Michaeli** *Novel phases in topological superconducting quantum dots*	0 h 45
12:45	**Lunch and free time**	3 h 45
16:30	**Oleg Astafiev** *Coherent quantum phase slips in superconducting materials*	0 h 45
17:15	**Thomas Weissl** *Charge localization in an inductive environment*	0 h 45
18:30	**Depart for dinner in a mountain refuge**	

Thursday 13 February

8:30	**Christoph Strunk** *Size-dependent conduction as a probe of long-ranged Coulomb interactions near the superconductor-insulator transition*		0 h 45
9:15	**Tatiana Baturina** *Superconductor-superinsulator transition in thin films: NbTiN versus TiN*		0 h 45
10:00	**Thierry Klein** *Thickness dependence of the superconducting critical temperature in boron doped silicon and diamond films*		0 h 45
10:45	**Coffee break**		0 h 30
11:15	**François Couëdo** *Disorder-tuned quantum phase transitions in a-*Nb_xSi_{1-x} *thin films*		0 h 45
12:00	**Vladimir Kravtsov** *Cooling of hot electrons in strongly disordered conductors: a giant enhancement of cooling rate by magnetic field*		0 h 45
12:45	**Lunch and free time**		3 h 45
16:30	**Coffee break**		0 h 30
17:00	**Boris Altshuler** *Title to be announced*		0 h 45
17:45	**Yigal Meir** *Superconductor-insulator transition in disordered thin films*		0 h 45
18:30	**Lara Benfatto** *Berezinskii-Kosterlitz-Thouless physics at the verge of the superconductor-insulator transition*		0 h 45
19:30	**Dinner**		1 h 30



Friday 14 February

8:30	**Stefano Gariglio** *Electric and magnetic field-tuned superconductor-to-insulator transition at the $LaAlO_3/SrTiO_3$ interface*	0 h 45
9:15	**Sudhansu S. Mandal** *Amplitude fluctuations due to shell-like effect in the strongly disordered superconductors with emergent granular structures*	0 h 45
10:00	**Zheng Han** *Collapse of superconductivity in graphene decorated by diluted triangular arrays of superconducting dots*	0 h 30
10:30	**Coffee break**	0 h 30
11:00	**Shimpei Ono** *Surface orientation dependence of an electric field induced superconductivity in $SrTiO_3$*	0 h 45
11:45	**Konstantin Tikhonov** *Fluctuation conductivity in the normal state of the hybrid array*	0 h 45
12:30	**Lunch and end**	1 h 30

Abstracts

Session 1 - Monday 10 - 08:30

Duality near the superconductor- insulator transition

Dan SHAHAR

Weizmann Institute (Israël)

Careful transport measurements near the superconductor-insulator transition in amorphous indium-oxide reveal a symmetry relating states in the insulator to those in the superconducting phase. I will discuss this symmetry and its consequences, and show that it is violated upon entering the strong insulator at low temperatures.

Session 1 - Monday 10 - 09:15

Amorphous nano-honeycomb film investigations of disorder effects on the SIT and transport deep in the Cooper pair insulator phase*

James M. VALLES, Jr.
with Shawna HOLLEN, Hung NGUYEN, Gustavo FERNANDEZ, Jeff SHAINLINE and Jimmy XU

Brown University, Providence, Rhode Island (USA)

While Bose insulator phases can be reliably produced in a few different thin film systems, many questions remain, like what drives the localization and controls the transport. Our group has been creating Bose insulators using ultrathin films patterned with an approximately triangular array of holes that have attractive features for addressing such questions. The patterning is accomplished by quench depositing the films onto the surface of nano-porous Anodized Aluminum Oxide substrates. Thus, it is possible to tune the thickness and thus, the normal state sheet resistance of the films continuously. At a critical thickness, dSIT, the films undergo a bosonic, Cooper Pair Insulator to superconductor transition (SIT) with increasing thickness. The hole array creates other interesting effects. The CPI phase is apparent from magneto-resistance oscillations that have a period corresponding to a superconducting flux quantum per unit cell of the hole array. For the superconducting films ($d>d_{SIT}$) the magneto-resistance oscillations can give rise to multiple SIT's. In this talk, I will present evidence of a new transport regime on our thinnest films deep in the CPI phase. I will also present how hole array disorder influences the thickness tuned and magnetic field tuned SIT's in these films.

*We are grateful for the support of the NSF Division of Materials Research.

Session 1 - Monday 10 - 10:00

Superconductor- metal transitions in 2D

Mikhail FEIGEL'MAN

L.D.Landau Institute for Theoretical Physics, Moscow (Russia)

I will review a number of experiments demonstrating quantum phase transitions from superconducting state to a highly conductive metal state at T=0 limit, upon increase of disorder at zero magnetic field.

Then I provide a review of relevant theoretical results on suppression of superconductivity in 2D metal films and proximity-coupled arrays. Finally, I will discuss theory status of the general problem of Superconductor-Metal QPT in 2D.

Session 1 - Monday 10 - 11:15

Cascade of phase transitions near quantum critical point

Konstantin EFETOV

Ruhr University Bochum (Germany)

In the standard picture of a quantum phase transition, a single quantum critical point separates the phases at zero temperature. Here we show that the two-dimensional case is considerably more complex. Instead of the single point separating the antiferromagnet from the normal metal, we have discovered a broad region between these two phases where the magnetic order is destroyed but certain areas of the Fermi surface are closed by a large gap. This gap reflects the formation of a novel quantum state characterized by a superposition of d-wave superconductivity and a quadrupole density wave (QDW), which builds a checkerboard pattern with a period incommensurate with that of the original spin density wave. At moderate temperatures both orders co-exist over comparatively large distances but thermal fluctuations destroy the long-range order. Below a critical temperature the fluctuations are less essential and superconductivity becomes stable. Applying a magnetic field destroys the superconductivity but establishes QDW. In addition to these phases we obtain also a charge density wave (CDW) arising as a result of interaction of electrons with superconducting fluctuations. This phase is possible when the superconductivity is destroyed by either thermal fluctuations or a magnetic field. The results of our theory can serve as explanation of recent experiments on cuprates performed with the help of STM, NMR, hard and resonant soft X-ray scattering, sound propagation, and with some other techniques.

Session 1 - Monday 10 - 12:00

Insulator- superconductor phase transition in crystalline metastable materials

Julius RANNINGER

Institut NÉEL, CNRS-Université Grenoble Alpes, Grenoble (France)

The cuprate high T_c superconductors, built out of incompatible stereo-chemical molecular clusters making up the metallic CuO_2 layers, exhibit a high temperature parent state which is electronically as well as lattice dynamically metastable. Its signature is a non-Fermi liquid, which we can picture in form of diamagnetic electron pairs popping in and out of existence of an underlying Fermi sea of itinerant electrons. We account for such a situation in terms of a Feshbach resonance coupling between bound and unbound electron pairs, embedded in the Fermi sea. On the basis of a generic Boson-Fermion model, we illustrate, how, upon lowering the temperature, a local dynamical symmetry breaking takes place in the parent state, which results in a local in space quantum superposition of bound and unbound electron pairs with finite local amplitude. It is this which generates the pseudogap state. Upon further reducing the temperature, those composite bosonic entities of the pseudogap state condense below some critical temperature in a spatially phase correlated superconductor above a certain critical carrier concentration. Below that, separated by a quantum phase transition, the system becomes an insulating phase uncorrelated Bose-glass state. We shall illustrate, on the basis of a Ginzbug Landau Functional formalism, adapted to such metastable systems which is controlled by the physics of Josephson junction arrays, that this quantum transition derives from an off-set charge term in the Lagrangian, generated by the fluctuating density of bound and unbound electrons pairs and which competes with the Josephson inter-site phase coupling.

Session 2 - Monday 10 - 17:00

Microwave spectroscopy evidence of superconducting pairing in the magnetic- field- induced metallic state of InO_x films at zero temperature

Peter ARMITAGE

Johns Hopkins University, Baltimore (USA)

We investigate the field-tuned quantum phase transition in a 2D low-disorder amorphous InO_x film in the frequency range of 0.05 to 16 GHz employing microwave spectroscopy. In the zero-temperature limit, the ac data are consistent with a scenario where this transition is from a superconductor to a metal instead of a direct transition to an insulator. The intervening metallic phase is unusual with a small but finite resistance that is much smaller than the normal state sheet resistance at the lowest measured temperatures. Moreover, it exhibits a superconducting response on short length and time scales while global superconductivity is destroyed. We present evidence that the true quantum critical point of this 2D superconductor metal transition is located at a field B_{sm} far below the conventionally defined critical field B_{cross} where different isotherms of magnetoresistance cross each other. The superfluid stiffness in the low- frequency limit and the superconducting fluctuation frequency from opposite sides of the transition both vanish at $B \sim B_{sm}$. The lack of evidence for finite-frequency superfluid stiffness surviving B_{cross} signifies that B_{cross} is a crossover above which superconducting fluctuations make a vanishing contribution to dc and ac measurements.

Session 2 - Monday 10 - 17:45

Collective modes in disordered superconductors

Aviad FRYDMAN

Department of Physics, Bar Ilan University, Ramat Gan 52900 Israel

In my talk I will discuss possible experimental evidence for collective effects in disordered superconductors. The disorder-driven superconductor-insulator transition (SIT) is considered to be a prototype of a quantum phase transition at zero temperature. Recently it has been suggested that collective modes known as Higgs and Goldstone modes can be detected in the vicinity of such a quantum phase transition, although they cannot be observed in clean, conventional superconductors.

For the detection of such modes we have performed spectroscopic measurements of disordered superconductors in the vicinity of the SIT by two different experimental methods: The first is tunneling spectroscopy which is sensitive to single particle excitations and the second is THz spectroscopy which can probe collective excitations as well. For clean superconductors the two methods yield similar results. Close to the transition, however, they strongly differ from each other. We ascribe this to the effect of collective excitations, and thus the comparison between these methods may significantly improve the understanding of the different excitations close to the SIT. I will discuss the results and their possible consequences.

Session 2 - Monday 10 - 18:30

Superconducting micro- resonators for radiation detection

Alessandro MONFARDINI

Institut NÉEL, CNRS-UJF, Grenoble

Superconducting resonators are classical devices used since the 1960s. It was however only about ten years ago that high performances micro-resonators, realised using thin films technologies, have been practically demonstrated. In the easiest configuration, the detector consists merely in a single, but properly patterned, film. Superconductivity ensures both the ultra-low losses needed to achieve high quality factors and the sensitivity to incoming radiation thanks to the kinetic inductance effect. In order to fulfil the growing number and variety of applications, new superconducting materials are under study. In this talk, starting from basic detection principles, I will summarize the recent achievements in this exciting and competitive field. This includes for example millimetre and sub-millimetre detectors for Astronomy, visible-NIR photon-counting cameras, high-energy photon/particles imagers. In conclusion, from a pure instrumentalist point-of-view, I elaborate a wish list of films characteristics that would permit a further spread of this already powerful and friendly detection technique.

Session 3 - Tuesday 11 - 08:30

Emergence of nanoscale inhomogeneity in the superconducting state of a homogeneously disordered s-wave superconductor

Pratap RAYCHAUDHURI

Tata Institute of Fundamental Research, Mumbai (India)

The notion of spontaneous formation of an inhomogeneous superconducting state is at the heart of most theories attempting to understand the superconducting state in the presence of strong disorder. Using a combination of scanning tunneling spectroscopy and high resolution scanning transmission electron microscopy, we experimentally demonstrate that under the competing effects of strong homogeneous disorder and superconducting correlations, the superconducting state of a conventional superconductor, NbN, spontaneously segregates into domains. Tracking these domains as a function of temperature we observe that the superconducting domains persist across the bulk superconducting transition, T_C, and disappear close to the pseudogap temperature, T*, where signatures of superconducting correlations disappear from the tunneling spectrum and the superfluid response of the system. These results along with complementary measurements of the superfluid stiffness at microwave frequencies underpins the importance of phase fluctuations in strongly disordered s-wave superconductors.

Session 3 - Tuesday 11 - 09:15

Disorder and Coulomb interactions in quasi two dimensional superconductors

Hermann SUDEROW

Universidad Autónoma de Madrid (Spain)

Scanning tunneling microscopy and spectroscopy has been shown to be a powerful tool to study crystalline and disordered very thin superconductors. Experiments have shown superconductivity in layers of in-situ grown films of simple metals, and in polycrystalline and amorphous thin films. In the former, disorder produces strong changes in the tunneling conductance vs bias voltage. In this talk, I will review these results briefly and discuss recent experiments made in sheets of transition metal dichalcogenides and in disordered thin films. Single and few layer sheets favor the appearance of a strong zero bias anomaly pointing to unconventional superconductivity. In thin films, we compare the resistive phase under magnetic field with the zero field phase and study spatial correlations between electronic disorder and superconductivity.

Session 3 - Tuesday 11 - 10:00

Tunneling spectroscopy of localized preformed Coopers pairs in highly disordered superconducting Indium oxide films

C. CHAPELIER[1], T. DUBOUCHET[1], B. SACÉPÉ[1,2], M. SANQUER[1], M. OVADIA[3], D. SHAHAR[3], M. FEIGELMAN[4] and L. IOFFE[5]

1. SPSMS, UMR-E 9001, CEA-INAC/UJF, Grenoble (France)
2. Institut NÉEL, CNRS-UJF, Grenoble (France) – 3. Weizmann Institute of Science, Rehovot (Israel)
4. Landau Institute for Theoretical Physic, Moscow (Russia) – 5. Rutgers University, New Jersey (USA)

We have performed tunneling spectroscopy on superconducting indium oxide films in the vicinity of the disorder-driven superconductor-insulator transition. Tunneling spectroscopy highlights a pseudogap regime above the critical temperature T_C which is the signature of preformed Cooper pairs. It evolves at low temperature into an inhomogeneous superconducting system due to spatial fluctuations of the disorder at the mesoscopic scale. These preformed Cooper pairs can locally remain localized at zero temperature. We showed that the absence of BCS coherence peaks at the gap edges in the local one particle density of states is the signature of these localized Cooper pairs[1]. Besides, using our STM, we have continuously analyzed the local conductance between the tunneling regime and the point-contact regime. In the latter, Andreev spectroscopy reveals a new energy scale related to the quantum coherence energy and independent from spatial fluctuations of the pairing energy[2].

[1] B. Sacépé, *Nature Physics* 7, 239 (2011).
[2] T. Dubouchet, in preparation.

Session 3 - Tuesday 11 - 11:00

Spectroscopic properties of ultrathin NbN films close to the superconductor–insulator transition

C. CARBILLET[1], V. CERCHEZ[1], C. BRUN[1], T. CREN[1], F. DEBONTRIDDER[1], D. RODITCHEV[1,2], B. LERIDON[2], K. ILIN[3], M. SIEGEL[3]

1. Institut des Nanosciences de Paris (INSP), Université Pierre et Marie Curie (France)
2. Laboratoire de Physique et d'Étude des Matériaux (LPEM), ESPCI, Paris (France)
3. Institute of Micro- und Nano-electronic Systems, Karlsruhe Institute of Technology, Karlsruhe (Germany)

In order to get a better understanding of the various processes taking place at the superconductor-insulator transition (SIT), we have probed the local and global electronic properties of NbN ultrathin superconducting films grown by magnetron sputtering[1]. We addressed the SIT using scanning tunneling spectroscopy measurements. The transition was approached by varying the thickness of ultrathin NbN films from 15nm down to 2.16nm, with corresponding Tc varying from 15K to 6.7K. Our STS data reveal profound changes in the local behavior of the superconducting films as the SIT is approached[2]. We observe a progressive decrease of the coherence peak height and small spatial inhomogeneities of the superconducting gap (e). Moreover, the gap below Tc develops on a spectral background which becomes more and more "V-shape" due to an Altshuler-Aronov correction in the tunneling density of states. In magnetic field, the spectroscopic contrast between vortex cores and regions between vortices diminishes strongly with Tc reduction. In this first set of experiments the STM and transport measurements were done separately. Due to the sample aging between the measurements it was not possible to measure if the disappearance of vortices in STM imaging was directly connected to the loss of global phase coherence as probed by transport measurements.

Thus we have pursued investigating the SIT problem in NbN thin films by combining transport measurements and mapping of the local density of states by STM. We have studied the spectroscopic characteristics of a nominally 2.14nm thick NbN sample, with a critical temperature of 4.1K, by varying both the temperature and the magnetic field in order to probe the entire (T-B) phase diagram. We succeeded to stay at the same sample area of about 300nmx300nm during all the experiment. The temperature was varied from 300mK to 7K and we applied a magnetic field up to 8T. We could observe the spatial evolution of the granular spectroscopic superconducting properties with temperature and magnetic field. We could also investigate the B-T behavior of the pseudogap regime of this highly disordered superconductor.

[1] A. Semenov et al., *Physical Review* B 2009, 80, 054510.
[2] Y. Noat et al., *Physical Review* B 2013, 88, 014503.

Session 3 - Tuesday 11 - 11:45

Emergent granularity, robust Cooper pairs, and spectroscopies across the superconductor-insulator transition

Nandini TRIVEDI

Ohio State University (USA)

I will discuss our theoretical and numerical results on the disorder-driven superconductor-insulator transition that predict the existence of a novel insulator of pairs.

We find that the single particle gap and optical conductivity evolve in unexpected ways across the transition and are supported by recent scanning tunneling spectroscopy and THz conductivity experiments.

Reference:

K. Bouadim, Y. L. Loh, M. Randeria and N. Trivedi, "Single- and two-particle energy gaps across the disorder-driven superconductor–insulator transition", *Nature Physics* 7, 884-889 (2011).

Session 4 - Tuesday 11 - 17:00

Current patterns and optical conductivity in disordered superconductors

Claudio CASTELLANI

Dipartimento di Fisica, Università di Roma "La Sapienza" (Italy)

Ioffe and Mezard have recently proposed a replica-symmetry breaking phase in disorder superconductors using a cavity method approach. Here we study the disordered attractive Hubbard model by solving the BdG equations on two- dimensional finite clusters at zero temperature By analyzing the on-site order parameter distribution (OPD) we find anomalous tails, with "typical" values much less than "averaged" values, which agree qualitatively with the predictions based on the presence of a broken replica-symmetry phase and suggests the relevance of the 2d Directed Polymer physics at strong disorder. By coupling the sample to an external field we find that the current density is strongly inhomogeneous with almost one- dimensional patterns. The optical conductivity besides the quasi-particle contribution shows an intra-gap absorption due to collective modes which appears to follow the same temperature dependence of the superfluid density.

References:

L. Benfatto, G. Seibold, J. Lorenzana and C. Castellani, "Superfluid density and phase relaxation in superconductors with strong disorder " DOI: 10.1103/*PhysRevLett.*108.207004 (2012).

G. Lemarie, A. Kamlapure, D. Bucheli, L. Benfatto, J. Lorenzana, G. Seibold, S. C. Ganguli, P. Raychaudhuri and C. Castellani, "Universal scaling of the order-parameter distribution in strongly disordered superconductors", DOI: 10.1103/*PhysRevB*.87.184509 (2013).

Session 4 - Tuesday 11 - 17:45

Microwave electrodynamics and local tunnelling spectroscopy of strongly disordered superconducting thin films

Eduard DRIESSEN

CEA, Grenoble (France)

We have studied the electrodynamic response of strongly disordered TiN and NbTiN films, close to the superconductor-insulator transition, by making the superconducting film the resonating element of a high-quality coplanar waveguide resonator at GHz frequencies. We study the temperature dependence of the resonator response, and find that with increasing disorder, the response increasingly deviates from conventional Mattis-Bardeen theory. Our measurements are well described with a uniform model of the superconducting state, using an effective pair breaker analogous to the effect of magnetic impurities, yielding a rounded-off quasiparticle density of states, analogous to the model of Feigel'man and Skvortsov[1]. The effective pair breaker needed to describe our measurements increases with increasing disorder.

We compare these observations to local scanning tunnelling spectroscopy on the same films. For the least-disordered film ($k_F l$ = 8), we find good agreement between the electrodynamics and the STS measurements. This indicates that disorder has already a pronounced influence on the superconducting state far away from the SIT, in contrast to what is commonly believed.

For the most-disordered film, $k_F l$ = 0.8, we find an inhomogeneous superconducting state, with larger coherence peaks and a steeper gap edge, than predicted from the electrodynamics measurement. This calls for a better theoretical understanding of the electrodynamics of strongly disordered superconductors.

[1] Feigel'man and Skvortsov, PRL 109, 147002 (2012).

Session 4 - Tuesday 11 - 18:30

Electromagnetic response of strongly disordered superconducting films

Mikhail SKVORTSOV and M. V. FEIGEL'MAN

L. D. Landau Institute for Theoretical Physics, Chernogolovka (Russia)

There is an experimental evidence that in many disordered superconducting films the order parameter exhibits strong fluctuations even if the system is far from the localization transition. Such strong inhomogeneities of the superconducting state cannot be explained by homogenously distributed impurities (primary disorder), and one should phenomenologically assume another source of fluctuations (secondary disorder). The role of the primary disorder is then to establish electron diffusion, while the secondary disorder is responsible for strong fluctuations in the superconducting state. Quite generally, scattering on the secondary disorder generates an effective depairing, similar to the one in the Abrikosov-Gorkov model of magnetic impurities. It leads to the smearing of the coherence peak which can be directly seen in an STM experiment. The secondary disorder also modifies the electromagnetic response of a superconductor that can no longer be described by the Bardeen-Mattis formulae. We calculate the superfluid density in the presence of the secondary disorder.

The resulting expression can be interpreted in terms of the Abrikosov-Gorkov theory, but the effective depairing is different from the one needed to fit the STM data.

Session 5 - Wednesday 12 - 08:30

Macroscopic tunneling of double phase slips in superconducting nanostructures

Alexey BEZRYADIN
with A. BELKIN, M. BELKIN, V. VAKARYUK, and S. KHLEBNIKOV

University of Illinois (USA)

Practical realization of quantum computing relies on a robust large-scale realization of a quantum superposition state and on tunneling in qubits. Such realization is difficult to achieve due to decoherence caused by the environment. It has been suggested that a qubit can be made topologically protected from decoherence by exploiting various parity effects. In particular, the double-phase-slip effect can provide topological protection for superconducting qubits. I will describe our observations of quantum double phase slips in thin-wire superconducting loops. We show that, in addition to conventional single phase slips, which change the phase of the superconducting order parameter by 2π and the vorticity of the loop by one, there are quantum transitions changing the phase by 4π and the vorticity by two. Both types of phase slips occur at low temperatures by means of macroscopic quantum tunneling. We demonstrate the existence of a striking regime in which double phase slips are exponentially more probable than single phase slips, which might provide grounds for future designs of topologically protected qubits.

Session 5 - Wednesday 12 - 09:15

Superconductor-Insulator Transition in Long Nanowires

Andrey ROGACHEV

Department of Physics and Astronomy, University of Utah (USA)

Superconductivity in one-dimensional wires can be affected by several physical processes with different characteristic length scales. To identify a process dominant in the regime of complete superconductivity suppression we studied transport properties of very narrow (9–20 nm) MoGe wires fabricated by advanced electron-beam lithography in a wide range of lengths, 1–25 micromrters. We observed that the wires undergo a superconductor-insulator transition (SIT) that is controlled by cross sectional area of a wire and possibly also by the width-to-thickness ratio. The mean-field critical temperature decreases exponentially with the inverse of the wire cross section. We observed that a qualitatively similar SIT can be induced by an external magnetic field. A zero bias anomaly in differential nonlinear resistance was observed. The anomaly changes sign from negative to positive exactly at the critical point of SIT driven by reducing cross sectional area as well as by magnetic field. No evidence of quantum phase slips was found. Our results are not consistent with any currently known theory describing suppression of superconductivity in 1D. Some of our long wires can be identified as Anderson superconductors.

Session 5 - Wednesday 12 - 10:00

Insulating state of a quasi-1D superconductor stimulated by quantum phase slippage

J. S. LEHTINEN, T. RANTALA and K. Yu. ARUTYUNOV

University of Jyväskylä, Department of Physics, NanoCentre, Jyväskylä (Finland)

The topic of quantum fluctuations in quasi-1D superconductors, also called quantum phase slips (QPS), has recently attracted the significant attention. It has been shown that the phenomenon is capable to suppress the zero resistivity of ultra-narrow superconducting nanowires at low temperatures $T<<T_c$ [1-3] and quench persistent currents in tiny nanorings[4]. The coherent QPS effect enables fabrication of the new generation of quantum logic devices – qubits[5]. It has been predicted that a superconducting nanowire in the regime of QPS is dual to a Josephson junction[6]. In particular case of an extremely narrow superconducting nanowire imbedded in high-impedance environment the duality leads to an intuitively controversial result: the superconductor should enter an insulating state. Here we experimentally demonstrate that the I-V characteristic of such a wire indeed shows Coulomb blockade which disappears with application of a critical magnetic field and/or above the critical temperature proving that the effect is related to superconductivity[7]. Such system can be considered as a junctionless single electron transistor (with charge 2e), where the QPS provide the dynamic equivalent of weak links in conventional devices containing static (in space and time) tunnel junctions. Application of external RF radiation can be synchronized with the internal Bloch oscillations of charge. The phenomenon is dual to the well-known Shapiro effect: the voltage steps for a Josephson junction are substituted by the current steps for a QPS wire: the proof-of-principle demonstration of the long-awaited metrological application - the quantum standard of electric current[8].

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[3] M. Zgirski, K.-P. Riikonen, V. Touboltsev and K. Yu. Arutyunov, *NanoLett*. 5, 1029 (2005); M. Zgirski, K.-P. Riikonen, V. Touboltsev and K.Yu. Arutyunov, *Phys. Rev. B*. 77, 054508 (2008); J. S. Lehtinen, T. Sajavaara, K. Yu. Arutyunov, M. Yu. Presnjakov and A. Vasiliev, *Phys. Rev. B* 85, 094508 (2012).

[4] K. Yu. Arutyunov, T. T. Hongisto, J. S. Lehtinen, L. I. Leino and A. L. Vasiliev. *Nature: Sci. Rep*. 2, 293 (2012).

[5] O. V. Astafiev, L. B. Ioffe, S. Kafanov, Yu. A. Pashkin, K. Yu. Arutyunov, D. Shahar, O. Cohen, & J. S. Tsai, *Nature* 484, 355 (2012).

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[7] J. S. Lehtinen, T. Rantala and K. Yu. Arutyunov, *arXiv.1311.3202* (2013).

[8] J. Lehtinen, K. Zakharov and K. Arutyunov, *Phys. Rev. Lett.* 109, 187001 (2012).

Session 5 - Wednesday 12 - 11:15

Quantum phase transitions in Josephson junction chains and ladders

Lev B. IOFFE

Rutgers University, New Jersey (USA)

I discuss the problem of the superconductor-insulator transition in one dimensional Josephson junction structures. I will show that the presence of the ubiquitous random charges which is so detrimental for conventional Josephson junction chains does not affect some special Josephson ladders so that the transition in these ladders can be mapped to the Ising or XY quantum critical models. I will show the experimental results by Gershenson group that borne out the theoretical predictions on the nature of the low energy excitations in these systems: Majorana fermions in case of the Ising model and fermions in case of the XY model. I will discuss the effect of a non-zero temperature on this transition and the phase diagram. I will show that at high temperatures a novel insulating state is formed and discuss the possibility of its experimental observation.

Session 5 - Wednesday 12 - 12:00

Novel phases in topological superconducting quantum dots

Karen MICHAELI

Massachusetts Institute of Technology, Cambridge (USA)

Recent progress in realizing topological superconductors has paved the road to study new physical phenomena resulting from the non-abelian statistics of the Majorana modes they host. A particularly interesting situation arises when Majorana bound states in a closed topological superconducting dot are coupled to external normal leads. In this talk, we will show that interactions with the quantum dot drive the lead electrons into a non-Fermi liquid phase, which can be understood by mapping the problem to a variant of a Kondo system. Interestingly, the non-Fermi liquid states in these systems are more robust than in the conventional two channel Kondo problem. This is because realizations with different numbers of metallic leads are connected to each other by a line of fixed points. We will conclude with a discussion of the experimental consequences of our theory.

Session 6 - Wednesday 12 - 16:30

Coherent Quantum Phase Slips in superconducting materials

Oleg ASTAFIEV

NEC Green Innovation Research Laboratories, Tsukuba (Japan)

Thermal fluctuations in superconducting wires in vicinity of the critical temperature cause random instantaneous suppression of superconductivity. This effect is known for a long time as incoherent slips of superconducting phase and can be observed as a finite voltage along the wire. The question if the phase slips can take place at absolute zero temperature, revealing quantum nature, remained open for a long time. In superconducting loops each phase slip event will be accompanied by the magnetic flux tunneling across the wire. The coherent flux tunneling, known also as the coherent quantum phase slip (CQPS), will be exactly dual to the Josephson Effect – tunneling of Cooper pairs between two superconductors across an insulating gap. In our recent experiments, we demonstrate superposition of fluxes in superconducting loops with a nano-wire due to the magnetic flux tunneling tunneling. The device represents so called CQPS qubit – dual analog of the charge qubit – is fabricated in highly disordered superconducting films and measured at temperatures below 50 mK. The experimental realization of CQPS opens perspectives of developing new types of devices dual to the Josephson ones. We perform the microwave spectroscopy of the CQPS qubits and demonstrate a finite energy splitting at the flux degeneracy points. The splitting is determined by the flux tunneling energy called also the phase-slip energy. In addition, we demonstrate universality of the effect reproducing it in thin highly disordered films of different materials such as InO, NbN and TiN. We also measure the wire width dependence of the phase-slip energy proving tunneling nature of the phenomenon.

Session 6 - Wednesday 12 - 17:15

Charge localization in an inductive environment

T. WEISSL, G. RASTELLI, I. MATEI, B. KUENG, A. FEOFANOV, E. DUMUR, O. BUISSON, F. W. HEKKING, W. GUICHARD

Grenoble University-CNRS, Grenoble (France)

In Josephson junctions, phase and charge are quantum conjugate variables. Depending on the ratio between charging energy and Josephson energy, either charge or phase fluctuations will dominate the dynamics of the junction. In the past, highly resistive environments have been used to reduce charge fluctuations in small Josephson junctions.

In this work we present measurements of a small Josephson junction in an inductive environment. We observe the appearance of a highly resistive state that can be explained by the localization of a wave packet in a charge potential. This potential originates from quantum phase slips occurring on the Josephson junction. We study the charge localization properties for different inductive environments. The finite resistance of the samples can be understood in terms of diffusion of the wave packet in the charge potential.

Session 7 - Thursday 13 - 08:30

Size-dependent Conduction as a Probe of Long-Ranged Coulomb Interactions near the Superconductor/Insulator Transition

Christoph STRUNK

Institute of Experimental and Applied Physics, University of Regensburg (Germany)

An investigation of the linear and non-linear conduction properties of square TiN films in the insulating regime is presented. A strong dependence on the lateral size L of the films is observed, when L varies between 0.5 and 500ɑm. This observation invalidates the concept of a local conductivity in our films. At temperatures below 1 K the conductance *G(T)* is thermally activated and the activation energy Δ_C grows logarithmically with L. We can relate this size dependence to long-ranged Coulomb interactions, which correspond to anomalously large values of the electrostatic screening length. Between 50mK and 150mK a size dependent saturation of G occurs, and below 50mK the *I(V)*-curves become non-linear for the largest samples. In the latter case we observe power laws $I \sim V^{\alpha}$ in the dc IV-characteristics with a strongly temperature dependent exponent α, which is a hallmark of the binding of charge/anti-charge pairs in presence of long-ranged interactions. The temperature below which the non-linearities occur agrees well with the independent estimate of the interaction energy extracted from the size dependent activation energy.

These observations point towards the importance of long-ranged two-dimensional Coulomb interactions in our films.

Session 7 - Thursday 13 - 09:15

Superconductor-Superinsulator Transition in thin films: NbTiN versus TiN

Tatyana I. BATURINA

A.V. Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk (Russia)

In this talk we will present a first experimental observation of the magnetic field induced superconductor-superinsulator transition in disordered thin NbTiN films. Perpendicular magnetic field drives the critically disordered superconducting film into an insulating state, which transits into a superinsulating one upon decreasing temperature. Appearance of the superinsulator is detected by the upturn from the Arrhenius-type temperature dependence of the resistance evidencing formation of the zero-conducting state at finite temperature.

Juxtaposing transport and superconducting properties of NbTiN with those of the earlier investigated TiN films, which demonstrate the superconductor-insulator transition and superinsulating state, we find that partial substitution of titanium by niobium results in a reduction of the carrier density and diffusion constant, increase of superconducting critical temperature and critical magnetic field, and characteristic temperatures of the magnetic-field-induced superconductor-superinsulator transition.

Session 7 - Thursday 13 - 10:00

Thickness dependence of the superconducting critical temperature in boron doped silicon and diamond films

T. KLEIN, A. GROCKOWIAK, J. BOUSQUET, E. BUSTARRET, F. CHIODI, D. DÉBARRE and C. MARCENAT

Institut NÉEL, CNRS-Université Grenoble Alpes, Grenoble (France)

In both boron doped silicon and diamond, superconductivity develops in the partially unlled valence band for boron concentrations $n_B > n_{cS}$. However, if the boron concentration corresponding to the onset of superconductivity (n_{cS}) coincides with that of the metal-insulator transition (MIT) in C:B, n_{cS} exceeds by several orders of magnitude n_{cMIT} in Si:B and the origin of this threshold value still has to be claried in this case. We will report on the superconducting properties of a series of heavily doped Si:B epilayers with Boron content ranging from 3.10^{20} cm^{-3} to 6.10^{21} cm^{-3} and thickness (d) varying between 20 nm and 210 nm. We show that n_{cS} actually scales as 1/d and, surprisingly, $T_c(n_B, d)$ is then fully determined by the n_Bxd product. A very similar decrease of T_c with d has been observed in C:B epilayers (30 nm < d < 1800 nm and n_B ~ $1.2.10^{21}$cm^{-3}). However, in contrast to this latter system for which the Ioffe-Regel parameter k_Fl ~ 1 (and a crossover to an insulating regime is observed as T_c vanishes), $k_Fl >> 1$ in Si:B and the destruction of T_c cannot be attributed to disorder in this case.

Session 7 - Thursday 13 - 11:15

Disorder-tuned quantum phase transitions in a-Nb_xSi_{1-x} thin films

François COUËDO

INSP, Paris (France)

In two dimensions, as the microscopic disorder is increased, superconducting films evolve toward an insulating state. This change in ground state has commonly been described as a direct Superconductor–to–Insulator Transition (SIT) and results from the competition between disorder-induced Anderson localization and the formation of a macroscopic superconducting coherent state.

a-Nb_xSi_{1-x} thin metal–alloy films are a model system to study the influence of disorder on superconductivity through a modification of composition, thickness or annealing. I will first present low temperature DC transport measurements performed on this material. We have evidenced non-predicted dissipative states resulting from the disorder-induced destruction of the superconducting long range order. Second, I will focus on a broadband microwave experimental setup we have developed, and the first measurements we have performed at low temperature to probe the electrodynamic response of disordered thin films.

Session 7 - Thursday 13 - 12:00

Cooling of hot electrons in strongly disordered conductors: a giant enhancement of cooling rate by magnetic field

V. E. KRAVTSOV

Abdus Salam ICTP, Trieste (Italy)

We consider energy transfer from hot electrons to phonon bath in strongly disordered conductors and Anderson insulators. We show that at strong disorder there is a general mechanism of cooling which is reminiscent of the Mandelstam-Leontovich relaxation in viscous liquids. We demonstrate the role of electro-neutrality in the cooling rate. We show that the presence of several species of electrons (such as valleys or spin directions) may greatly increase the cooling rate. We consider in detail the special case of cooling of spinful electrons in the external magnetic field and demonstrate a giant magneto-cooling effect: the increase of the cooling rate by several orders of magnitudes in magnetic field of few Tesla.

Session 8 - Thursday 13 - 17:00

Title to be announced

Boris ALTSHULER

Columbia University, New York (USA)

Session 8 - Thursday 13 - 17:45

Superconductor-Insulator Transition in Disordered Thin Films

Yigal MEIR

Ben Gurion University (Israël)

The interplay of disorder and superconductivity is one of the outstanding questions in condensed matter physics, especially at low dimensions, where fluctuations play a significant role. In this talk I will concentrate on the nature of the superconductor-insulator transition in disordered thin films, and its relation to the Berezinsky-Kosterlitz-Thouless transition on one hand, and percolation of coherence on the other. I will discuss a proposed experiment to explore the spatial correlations of the propagation of coherence near the transition, and, lastly, the emergence of superconducting coherence after a sudden quench from the insulating side.

Session 8 - Thursday 13 - 18:30

Berezinskii-Kosterlitz-Thouless physics at the verge of the superconductor-insulator transition

Lara BENFATTO

CNR, Institute for Complex Systems, Rome (Italy)

The experimental advances made in the last decade in the investigation of superconducting phenomena in low-dimensional correlated electronic systems raised new questions on the nature of the Beresinskii-Kosterlitz-Thouless (BKT) transition in quasi-two-dimensional superconductors. Here I will review recent theoretical[1] and experimental[2,3] work for the occurrence of BKT transition in two-dimensional (2D) disordered NbN films with disorder level very close to a superconductor-insulator transition (SIT). By properly taking into account the deviations of the vortex-core energy value from its XY-model prediction we can show that the BKT superfluid-density jump is robust even near this 2D disorder-tuned quantum critical point (QCP). At the same time, the dissipation peak around Tc measured by the real part of the optical conductivity gives crucial informations on the vortex dynamics, leading to unexpected results for the vortex diffusion constant[4]. All these results are discussed in connection to the emergent inhomogeneity of SC properties near the SIT evidenced by recent STM experiments[5].

[1] L. Benfatto, C. Castellani and T. Giamarchi, Chapter contribution for the book,*Berezinskii-Kosterlitz-Thouless Transition*", Edited by Jorge V. José, World Scientific (2013); arXiv:1201.2307.

[2] Mintu Mondal, Sanjeev Kumar, Madhavi Chand, Anand Kamlapure, Garima Saraswat, G. Seibold, L. Benfatto, Pratap Raychaudhuri, *Phys. Rev. Lett*. 107, 217003 (2011).

[3] Jie Yong, T. Lemberger, L. Benfatto, K. Ilin, M. Siegel, *Phys. Rev. B* 87, 184505 (2013).

[4] M. Santagata and L. Benfatto, in preparation.

[5] G. Lemarie, A. Kamlapure, D. Bucheli, L. Benfatto, J. Lorenzana, G. Seibold, S. C. Ganguli, P. Raychaudhuri and C. Castellani, *Phys. Rev. B* 87, 184509 (2013).

Session 9 - Friday 14 - 08:30

Electric and Magnetic field-tuned superconductor-to-insulator transition at the $LaAlO_3/SrTiO_3$ interface

S. GARIGLIO, A. FÊTE, D. LI, D. STORNAIUOLO, J.-M. TRISCONE

DPMC University of Geneva (Switzerland)

The conducting interface between the two band insulators $LaAlO_3$ and $SrTiO_3$ has drawn a large share of attention, as it presents a variety of exciting electronic properties that are tunable by an electric field[1]. At low temperatures, magnetotransport analysis has revealed a strong Rashba spin-orbit interaction originating from the breaking of inversion symmetry[2] and, in field effect devices, the ground state has been tuned from an insulating to a superconducting state[3].

I will discuss these results in light of recent experiments on nano-devices[4] to probe spectroscopically the superconducting gap and its evolution across the phase diagram. To this aim, using a patterning technique based on electron beam lithography, we realize nanodevices with width down to 200 nm where the use of a side-gate field effect approach allows the tuning of the superconducting state.

I will also present a study of the superconductor-to-insulator transition tuned by the magnetic field for different doping levels set by electric field-effect.

[1] P. Zubko, S. Gariglio, M. Gabay, P. Ghosez, J.-M. Triscone, Ann. Rev. Conden. *Matt. Phys*. 2, 141 (2011).

[2] A. D. Caviglia et al., *Phys. Rev. Lett*. 104, 126803 (2010); A. Fête et al., *Phys. Rev*. B 86, 201105 (2012). [3] A. D. Caviglia et al., *Nature* 456, 624 (2008). [4] D. Stornaiuolo et al., *Appl. Phys. Lett*. 101, 222601 (2012).

Session 9 - Friday 14 - 09:15

Amplitude fluctuations due to shell-like effect in the strongly disordered superconductors with emergent granular structures

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The shell effect in a nanoscale pure superconductor has recently been observed[1]. It is the oscillation of pairing amplitude due to a rapid change in the low energy spectral density which can be controlled by the density of electrons in small size superconductors. A tight binding lattice model with negative U Hubbard interaction and on-site disorder potential is one of the most studied model for disordered superconductors.

A self-consistent solution of the mean field Bogoliubov-de Gennes equations derived from this model suggests the formations[2] of nanosize superconducting puddles (SPs) with large pairing amplitudes (PA) separated by insulating regions at a very high disorder. We find[3] that the texture of the PA forming the SPs at large disorder, especially in the insulating side of the superconductor-to-insulator transition, undergoes a huge change with little change in average electron density, n, in spite of the unaltered landscape of disorder. We show evidence of shell-like effect because of the presence of emergent nanosize granular structures in the form of SPs in disorder superconductor, and that is responsible for the rapid change in the texture of PA as n is varied.

[1] S. Bose, A. M. Garcia-Garcia, M. M. Ugeda, J. Urbina, C. Michaelis, I. Brihuega and K. Kern, *Nat. Matter.* 9, 550 (2010).

[2] A. Ghosal, M. Randeria and N. Trivedi, *Phys. Rev. Lett.* 81, 3940 (1998); *Phys. Rev. B* 65, 014501 (2001).

[3] S. Ghosh and S. S. Mandal, *Phys. Rev. Lett.* 111, 207004 (2013).

[3] Adrien Allain *et al.*, *Nature Materials*, 11, 590–594, (2012).

Session 9 - Friday 14 - 10:00

Collapse of superconductivity in Graphene decorated by diluted triangular arrays of superconducting dots

Z. HAN[1], A. ALLAIN[1], H. ARJMANDI-TASH[1], K. TIKHONOV[2,3], M. FEIGEL'MAN[2,4], B. SACÉPÉ[1] , L. MARTY and V. BOUCHIAT[1]

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3. Dept. of Cond. Matt. Phys., The Weizmann Inst. of Science, Rehovot (Israel)

4. Moscow Institute of Physics and Technology, Moscow (Russia)

The easily accessible 2D electron gas offered by graphene provides an ideal platform on which to tune, via application of an electrostatic gate, the coupling between adsorbates deposited on its surface. This situation is particularly interesting when the network of adsorbates can induce some electronic order within the underlying graphene substrate, such as magnetic or superconducting correlations[1]. We have experimentally studied the case of macroscopic graphene decorated with an array of superconducting tin clusters[2], which induce via percolation of proximity effect a global but tunable 2D superconducting state. By adjusting the graphene disorder and its charge carrier density on one side , the geometry and size of the superconducting dot network on the other side, the superconducting state can exhibit very different behaviors, allowing to test different regimes and quantum phase transition from a granular superconductor to either metallic or insulating states[3]. We will show recent experimental results involving set of triangular arrays sparsely distributed on graphene, in which superconductivity is suddenly destroyed for a critical gate value due to quantum fluctuations of the phase, giving rise to an intermediate metallic state at the zero temperature limit[4].

[1] M. Feigel'man *et al.*, *JETP Lett.*, 88, 747, (2008).
[2] B.M.Kessler *et al.*, *Phys. Rev. Lett* 104, 047001 (2010).
[3] Adrien Allain *et al.*, *Nature Materials*, 11, 590–594, (2012).
[4] Zheng Han *et al.*, submitted (2013).

Session 9 - Friday 14 - 11:00

Surface orientation dependence of an electric field induced superconductivity in $SrTiO_3$

Shimpei ONO

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Electric-double-layer gating is attracting growing interest not only for applications but also for their new electric functions in electric double-layer transistors exemplified by high-performance organic electronics, field-induced electronic phase transitions, as well as superconductivity. Here we report surface orientation dependence of an electric field induced superconductivity in $SrTiO_3$. We found that superconducting critical parameters and gate bias dependence show different behavior on different surfaces.

Session 9 - Friday 14 - 11:45

Fluctuation conductivity in the normal state of the hybrid array

Konstantin TIKHONOV

Landau Institute for Theoretical Physics, Chernogolovka (Russia)

As was long ago predicted theoretically[1,2] and realized in recent experiments[3,4], mesoscopic superconductor-normal metal arrays exhibit phase transition from superconducting to normal state, which may be of quantum (with integrain conductance as a control parameter) or thermal origins. Interestingly, even above the transition, conductivity of the sample demonstrates strong dependence on the distance to the critical point. Motivated by these findings, we discuss fluctuation contributions to electrical conductivity of such an array in the normal state.

[1] M. V. Feigel'man and A. I. Larkin, "Quantum superconductor-metal transition in a 2D proximity coupled array", *Chem. Phys*. 235, 107-114 (1998).

[2] M. V. Feigel'man, A. I. Larkin and M. A. Skvortsov, "Quantum Superconductor-Metal Transition in a Proximity Array", *Phys. Rev. Lett.* 86, 1869-1872 (2001).

[3] S. Eley, S. Gopalakrishnan, P. Goldbart and N. Mason, "Approaching zero-temperature metallic states in mesoscopic superconductor-normal-superconductor arrays", *Nature Phys*. 8, 59-62 (2012).

[4] Zheng Han, Adrien Allain, Hadi Arjmandi-Tash, Konstantin Tikhonov, Mikhail Feigel'man, Benjamin Sacépé and Vincent Bouchiat, "Collapse of superconductivity in a hybrid tin-graphene Josephson junction array", to be published.

List of posters

Alireza Akbari ➪ P. 30
QPI in singlet, triplet and non-centrosymmetric unconventional superconductors

Olivier Bourgeois ➪ P. 29
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Scanning Tunneling Spectroscopy Study of the electronic properties of monolayer superconductors

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Spectroscopic properties of ultrathin superconducting NbN films close to the insulating transition

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Tuning material properties near the superconductor-insulator transition for coherent quantum phase-slip devices

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Temperature evolution of transport properties of superconducting TiN films

Uwe Pracht ➪ P. 36
Electrodynamics of superconducting thin films probed by frequency domain THz spectroscopy

Peter Samuely ➪ P. 33
Transport properties of ultrathin molybdenum carbide superconducting films near transition to insulating state

Johanna Seidemann ➪ P. 38
High field termination of a Cooper-pair insulator

Pavol Szabó ➪ P. 33
Scanning tunneling microscopy and spectroscopy of superconducting MoC ultra thin films

Sabyasachi Tarat ➪ P. 35
Tunneling spectroscopy across the superconductor-insulator thermal transition

Specific heat measurements of quench condensed granular Pb thin films

Shachaf PORAN[1,2], Anne GÉRARDIN[2], Aviad FRYDMAN[1] and Olivier BOURGEOIS[2]

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2. Institut NÉEL, CNRS and Université Grenoble Alpes, Grenoble (France)

A high vacuum evaporation chamber was designed to perform highly sensitive specic heat, C_p, measurements of quench condensed superconducting thin lms in the temperature range 1:5 – 10 K and in magnetic elds up to 1:5 T. The calorimetric sensor consists of a suspended silicon membrane on which a heater and a thermometer are pre-deposited allowing *in-situ* simultaneous thermal and transport measurements of quench condensed thin lms. This experimental apparatus permits, for the rst time, measurements of the specic heat signature of critical phenomena in ultra-thin superconductors (granular or continuous) as a function of lm thickness without having to warm up the sample. This provides a novel thermal approach for the study of the disorder induced superconductor-insulator-transition which diers from the standard transport techniques used in the past.

First results of heat capacity and transport measurements on granular lead are presented; more than 18th consecutive evaporations have been done. A peak in C_p is observed for lms with thickness of the order of tens of nanometers at temperatures very close to the resistive T_c. It should be noted that the specic heat anomaly at the transition appears only for thick lms. No apparent specic heat jump can be observed at a thickness corresponding to the insulating state. Further studies are underway aimed at measuring the specic heat in thinner lms (continuous or granular), especially in the presence of a Berezynski-Kosterlitz-Thouless transition.

Superconductor-Metal-Insulator transitions in two dimensional a-NbSi

V. HUMBERT, F. COUËDO, A.A. DRILLIEN, L. BERGÉ, L. DUMOULIN, C.A. MARRACHE-KIKUCHI

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Three dimensional amorphous Nb_xSi_{1-x} compounds exhibit disorder-driven Superconductor-Metal-Insulator Transitions. These transitions can be driven by different external parameters such as the composition x, the thickness, or by moderate annealing[1]. One can wonder what becomes of these transitions and of the corresponding ground states when the dimensionality of the system is reduced. Indeed, localization is believed to forbid any two dimensional metallic phase in the absence of strong Coulomb interactions[2].

In order to address this question, we have studied thin a-Nb_xSi_{1-x} films in the vicinity of the Superconductor-to-Insulator Transition that has previously been established in the two-dimensional limit in this material[3]. We more specifically focus on the disappearance of the insulating phase as the film disorder is lowered. We have conducted very low temperature transport measurements on such films and shown that the phase that emerges is compatible with the existence of a dissipative phase.

[1] L. Dumoulin, L. Bergé, J. Lesueur, H. Bernas and M. Chapellier, "Nb-Si thin films as thermometers for low temperature bolometers". *J. Low Temp. Phys*. 93 (3-4): 301-306 (1993).

[2] E. Abrahams, P.W. Anderson, D.C. Licciardello and T.V. Ramakrishnan, "Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions", *Phys. Rev. Lett.* 42 (10): 673–676 (1979).

[3] O. Crauste, A. Gentils, F. Couëdo, Y. Dolgorouky, L. Bergé, S. Collin, C.A. Marrache-Kikuchi and L. Dumoulin, "Effect of annealing on the superconducting properties of a-NbxSi1-x thin films". *Phys. Rev. B* 87:144514 (2013).

Scanning Tunneling Spectroscopy Study of the electronic properties of monolayer superconductors

C. BRUN[1], T. CREN[1], V. CHERKEZ[1], F. DEBONTRIDDER[1], S. PONS[1], L.B IOFFE[2], B.L. ALTSHULER[3], D. FOKIN[1], M. C. TRINGIDES[5], S. BOZHKO[6] and D. RODITCHEV[1,7]

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5. Ames Laboratory-U.S. Department of Energy and Department of Physics and Astronomy, Iowa State University (USA)
6. Institute for Solid State Physics, RAS 142432, Chernogolovka, (Russia)
7. LPEM-UMR8213/CNRS-ESPCI ParisTech-UPMC, Paris (France)

It was recently shown that is possible to grow single atomic monolayers of Pb on Si(111) which are superconducting below 2K as demonstrated by STS[1] and transport measurements[2,3]. As previous measurements have shown that these systems are BCS-like, we have re-investigated their local spectral properties. Surprisingly, our local STS measurements at atomic and mesoscopic scale on these ultimate 2D superconductors reveal new effects of local disorder on the superconducting properties going beyond BCS theory and Anderson theorem.

[1] T. Zhang *et al.*, 6, 104 *Nature Physics* (2010).
[2] T. Uchihashi *et al.*, *Phys.Rev. Lett.* 107, 207001 (2011).
[3] Y. Yamada *et al.*, *Phys. Rev. Lett.* 110, 237001 (2013).

QPI in singlet, triplet and non-centrosymmetric unconventional superconductors

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The technique of quasiparticle interference (QPI) has recently been successfully applied to heavy fermion compounds to determine the un- conventional superconducting gap symmetry. It was proposed[1] and proven[2,3] that QPI can distinguish between the d-wave singlet can- didates of superconducting $CeCoIn_5$. The QPI theory has now also been developed for non-centrosymmetric (NCS) superconductors[4] with mixed singlet-triplet gap function. Qualitatively new effects in the QPI pattern originate from Rashba spin-orbit coupling: Distinct differences between charge- and spin QPI and anisotropies appear due to additional Rashba coherence factors. We use Born approximation and full t-matrix theory to calculate the QPI spectrum and apply it to a 2D model for the NCS heavy fermion unconventional superconduc- tor $CePt_3Si$. We discuss the new QPI features for a gap model with accidental node lines due to its composite singlet-triplet nature. Furthermore we predict the quasiparticle interference spectrum for the multiband chiral p-wave superconductor Sr_2RuO_4[5] and the possible chiral d-wave superconductor.

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Spectroscopic properties of ultrathin superconducting NbN films close to the insulating transition

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In order to better understand the various processes taking place at the superconductor-insulator transition (SIT), we have probed the local and global electronic properties of NbN ultrathin superconducting films. Otherwise, the study of such films is particularly interesting for applications in single photons detectors. Especially, it has been recently demonstrated that the maximum detection efficiency occurs for stripes thicknesses close to the SIT. The structural properties of the films are shown to play a key role in determining the electronic properties at low temperature. The sample are elaborated ex-situ by our collaborators[1].

In our previous work, we addressed the SIT using scanning tunneling spectroscopy measurements. The transition was approached by varying the thickness of ultrathin NbN films from 15nm down to 2,16nm. The corresponding Tc diminish from 15K to 6,7K. Our STS data reveal profound changes in the local behavior of the superconducting films as the SIT is approached[2]. We observe a progressive decrease of the coherence peak height and small spatial inhomogeneities of the superconducting gap (e). Moreover, the gap below T_C develops on a spectral background which becomes more and more "V-shape" due to Altshuler- Aronov effect. In magnetic field, the spectroscopic contrast between vortex cores and regions between vortices diminishes strongly with T_C reduction. This features called for better controlled STS experiment coupled to transport ones to precisely know the macroscopic resistance state in B while performing STS.

Thus we have pursued investigating the SIT problem in NbN thin films by combining transport measurements[3] and local electronic properties by probing the local density of states by STS experiments. We have studied the spectroscopic characteristics of a nominally 2,14nm thick NbN sample, with a critical temperature of 4,1K, by varying both the temperature and the magnetic field in order to probe the entire (T- B) phase diagram. We succeeded to stay at the same sample area of about 300nmx300nm during all the experiment. The temperature was varied from 300mK to 7K and we applied a magnetic field up to 7T. We could observe the spatial evolution of the granular spectroscopic superconducting properties with temperature and magnetic field. We could also investigate the B-T behavior of the pseudogap regime of this highly disordered superconductor.

The magnetic field induced SIT or SIN was also studied by transport measurement in another ultrathin 2,16nm thick NbN film with a T_C of 6,1K. Assuming that a quantum transition occurs at the absolute zero of temperature, a finite size scaling analysis was carried out to determine the correlation length exponent ν and the dynamical critical exponent z. These two parameters determine the universality class of the transition[4]. In order to cross-check the values found for the exponents, we have also studied the effect of the electrical field[5].

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Tuning material properties near the superconductor-insulator transition for coherent quantum phase-slip devices

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The phenomenon of coherent quantum phase-slips in superconducting nanowires has promise for a number of devices, including a sensitive charge detector, a detector for small rf signals, a tunable capacitance and a quantum current standard[1]. Materials systems tunable to close to the superconductor-insulator transition are ideal for these nanowires since both superconductivity and a high normal-state resistance are important (although not the only considerations[2]) for nanowires to act as these quantum phase-slip elements. Experimentally, in microwave spectroscopy, qubit transitions have now been demonstrated associated with coherent quantum phase-slips in indium-oxide[3] and niobium-nitride nanowires[4], and earlier transport measurements in NbSi nanowires[5] also have shown the current blockade features expected with coherent quantum phase-slip. In this talk I will review developments in this field with respect to the materials systems and describe our ongoing work at UCL to realise coherent quantum phase-slip devices.

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Real Space Visualisation of Defect Annealing in a Disordered Vortex Lattice

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Using scanning tunnelling spectroscopy as a real space imaging technique, we investigate a variety of phases that emerges at low temperature in the flux-line lattice (FLL) of a Type II superconductor, $NbSe_2$. Each phase is characterised by different degree of positional order, which is quantitatively given by autocorrelation function. In the zero field cooled (ZFC) state, the FLL is almost perfectly hexagonal with very low degree of positional disorder. The field cooled (FC) state on the other hand is characterised by a proliferation of topological defects in the form of dislocations. We show that by applying very small magnetic field pulses we can annihilate the topological defects in the field cooled lattice. The resulting state however is distinct from the ZFC state. Even though there are no dislocations in the FLL of the annealed FC state, the positional disorder is high when distortion in FLL is significant over the scan area and viceversa. To summarise, the state prepared from FC state by applying magnetic field pulse (of any magnitude) is distinct from the ZFC state.

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Transport properties of ultrathin molybdenum carbide superconducting films near transition to insulating state

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A series of MoC films of different thicknesses from 20 nm down to 2 nm has been prepared via the reactive magnetron sputtering of Mo in a mixture of argon and acetylene on single-crystalline sapphire substrates. The structure of the samples was characterized by the X-ray diffraction and the surface morphology by AFM and STM. With decreasing thickness the superconducting transition temperature was systematically suppressed from 8 K down to 1 K followed by a transition into an insulating state. We will present the electrical transport properties including the magnetoresistance and the Hall effect. Different level of disorder in thin films will be characterized by their sheet resistance and the Ioffe–Regel product k_F*l, where k_F is the Fermi momentum and l is the electron mean free path determined from the transport measurements. The same samples were subsequently used for the subKelvin scanning tunnelling microscopy and spectroscopy measurements which are subject of another contribution at the conference.

Scanning tunneling microscopy and spectroscopy of superconducting MoC ultra thin films

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The experimental study of the superconductor-insulator transition will be presented on strongly disordered MoC ultrathin films. The increase of disorder is achieved by depleting their thickness down to 3 nm. Using scanning tunneling microscopy and spectroscopy in a ^{3}He refrigerator we addressed the topography and spectral maps of the superconducting density of states (SDOS) on the films with 10 nm, 5 nm and 3 nm thickness, with T_c = 5.6 K, 3.7 K and 1 K, respectively. The simultaneous measurements of surface topographies and CITS conductance maps will be presented at temperatures below 1 K. All measured films show a BCS-like SDOS with a significant broadening, which increases with increasing disorder. The results will be discussed in the context of the STM/S measurements published on other disordered superconductors close to the superconductor-insulator transition.

Universal scaling in thin superconducting films

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Superconductivity in thin films is a unique platform for geometrically-confined, strongly- interacting electrons. As such, it enables exotic phenomena that include quantum phase transitions and the Josephson effect. Furthermore, understanding the effect of miniaturisation on superconductivity has technological significance, e.g. for photo-detectors, and quantum- computers[1,2]. Consequently, a universal relation between critical temperature (T_c), film thickness (d) and sheet resistance at the normal state (R_s) has continuously been sought. Usually, T_c suppresses with decreasing thickness and increasing resistance. Traditionally, two alternative approaches have been used to describe this suppression; one argues that T_c depends on the thickness, while the other claims that T_c depends only on R_s, which represents the disorder in the system. For instance, the proximity effect[3] and the quantum size effect[4] models suggest that $T_c = T_c(d)$, whereas $T_c = T_c(R_s)$ was derived for the Kosterlitz-Thouless transition[5] and for homogeneous superconductors[6]. However, each of these models applies only to specific cases, while superconductivity is also still not fully understood in some thin amorphous or disordered films[7,8]. Moreover, in some cases, the critical temperature exhibits unexplained enhancement at reduced thicknesses[9,10].

We recently found a new scaling for superconductivity in thin films: $d{\cdot}T_c(R_s)$. We verified this scaling for both NbN films and the data published in the past 45 years for materials that differ in homogeneity, disorder, and bulk superconductivity-type (I or II). Hence, we demonstrated universality for a scale that spans more than four orders of magnitude for both Rs and d and an order of magnitude for T_c.

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Magneto-oscillations of the mobility edge in Coulomb frustrated bosons and fermions

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We study the crossover from strong to weak localization (effective mobility edge) of hard-core bosons on a two dimensional honeycomb lattice in the presence of Coulomb interaction and mag- netic field. Within the forward scattering approximation we find the effective mobility edge to oscillate periodically with the magnetic flux per plaquette. In contrast to the equivalent fermionic problem, the oscillations start with an increase of the mobility gap. The amplitude of oscillation is much more substantial for bosons than that for fermions.

Tunneling, dissipation, and superconductivity in percolating cluster films

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The Inert Gas Aggregation (IGA) technique allows nanoparticles to be prepared in the gas phase, mass selected, and deposited on a wide variety of substrates, including devices that have been lithographically engineered. We have demonstrated a number of methods for directed assembly of nanowires and for preparation of various nanoscale electronic devices, including gas sensors and transistor devices.

Here we will focus on devices that contain percolating films of Sn and Pb clusters, between a pair of electrical contacts, and especially those that are deliberately constructed so as to guarantee that the film is close to the percolation threshold (onset of conduction). In these devices quantum mechanical tunnelling is important, and several new and unexpected phenomena are observed. In particular we have recently demonstrated switching between well-defined, quantized, conductance values [multiples of the quantum of conductance ($2e^2/h$)], at room temperature.

At low temperatures the onset of superconductivity in these devices is controlled by the amount of disorder in the film and the percolating films have interesting characteristics that are intermediate between those of 1D and 2D systems. Both the R(T) and V(I) data show clear evidence for phase slips, which appear to occur in the narrow necks between clusters. The surface coverage of the films controls a transition between strongly hysteric, sharp V(I) curves and those with no hysteresis and very gradual transitions to the normal state. In the latter case the observed data is of the form $V \sim (I - I_C)n$, with $n \sim 2$, which is a consequence of percolation rather than a Kosterlitz-Thouless transition.Below the percolation threshold, transport between adjacent groups of particles is due to tunneling, and we observe a superconductor to insulator transition. It is particularly intriguing that this transition can be driven by the applied current.

Finally, we are exploring the transport between the superconducting films and the electrical contacts, where we see unusual behaviour that seems to be intermediate between that expected for Andreev reflection and tunnelling spectroscopy.

Tunneling spectroscopy across the superconductor-insulator thermal transition

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Recent scanning tunneling measurements reveal the presence of superconducting nano regions well past the bulk thermal transition in strongly disordered superconductors. We use a Monte Carlo scheme that captures the disordered superconducting ground state, and fully retains thermal amplitude and phase fluctuations, to describe the phase transition in such systems. Our results on transport suggest that at large disorder superconductivity can arise out of an insulating normal state, and the high temperature value of the low energy density of states correlates with the ground state superconducting fraction. Our detailed spatial maps of the coherence peak reveal that at large disorder superconducting regions shrink and fragment with increasing temperature but surive in small clusters much above T_c, while the insulating regions are insensitive to temperature. We identify a 'cluster survival' temperature and a 'gap persistence' temperature and discover that they are are related to distinct physical effects, the similar magnitude that is observed for them in recent experiments holds only at weak coupling.

Electrodynamics of superconducting thin films probed by frequency domain THz spectroscopy

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Quasi-optical THz spectroscopy is a particularly suited probe to study superconducting properties of thin films, such as the superconducting energy gap or superfluid density. With our THz-spectroscopy approach we measure amplitude and phaseshift of radiation (0.09-1.2 THz) passing through thin film systems using a set of backward-wave-oscillators (BWOs) as tunable monochromatic and coherent THz sources. We discuss the performance and possibilities of our experimental set-up, and we apply it to clean and disordered superconducting films of TiN, NbN and TaN. We fit the experimental data to a combination of Fresnel equations and BCS theory, and we obtain frequency- and temperature-dependent superconducting properties such as the complex optical conductivity, the complex dielectric function, the energy gap, the penetration depth, and the superfluid density. We discuss recent results obtained on strongly disordered NbN films pointing towards non-BCS behavior.

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Superfluid and transport properties of dirty Bosons in two dimensions

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We discuss the normal to superfluid transition of interacting Bosons in two dimensions under the influence of a correlated disorder potential[1]. Using path-integral Monte Carlo calculations we establish the phase diagram for homogeneous and trapped systems[2].

We show that the superfluid phase transition is strongly protected against disorder and its critical properties remain in the Kosterlitz-Thouless universality class. We further adress conductance properties in the strongly disordered regime at finite temperatures. Our numerical results indicate that the insulating behavior at large disorder amplitudes is well described by a thermally activated behavior of the Arrhenius type.

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Thickness-induced SIT in Boron doped diamond epilayers

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From an experimental point of view, the influence of the disorder on the superconducting to insulator transition (SIT) has been widely studied in both amorphous and granular systems, but remains fairly rare on crystalline materials. In this context, epitaxial Boron Doped Diamond is an original and promising playground to carry out such a study.

We have thus undertaken a detailed study of the disorder induced SIT by reducing the dimensionality of our system. To that aim, we have grown a series of epilayers with a fixed doping level of $1.5.10^{21}$ cm^{-3} (above the offset of both metalicity and superconductivity at $5.10^{20}cm^{-3}$) and thickness ranging between 30 nm and 2 αm.

We will first present the microwave plasma enhanced chemical vapor deposition process (MPCVD) used to grow the samples and discuss how this technique can fulfil the criteria required for this study; control of the doping level, crystalline quality but more importantly, an accurate control of the thickness.

Four point probe (from 300K down to 30mK) as well as magnetotransport measurements have been performed on the series of diamond epilayers and will be presented. We will show that our films can be considered as three-dimensional dirty superconductors (kFl≈2). The drop of the critical temperature observed under 150 nm will be discussed and confronted to various models. Finally, we will focus on the normal state properties and point out an increase of the electron-electron interaction close to the SIT.

Universal scaling of the order-parameter distribution in strongly disordered superconductors

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We investigate theoretically and experimentally the statistical properties of the inhomogeneous order-parameter distribution (OPD) at the verge of the superconductor-insulator transition (SIT). We find within two prototype fermionic and bosonic models for disordered superconductors that one can identify a universal rescaling of the OPD. By performing scanning-tunneling microscopy experiments in three samples of NbN with increasing disorder we show that such a rescaling also describes the experimental data with excellent accuracy.

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Temperature evolution of transport properties of superconducting TiN films

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The electron transport properties of thin (d ≤ 23 nm) TiN superconducting films have been studied experimentally in a wide range of temperatures.

We have found that with temperature decreasing the resistance of relatively thick (d ≥ 7 nm) films first decrease from room temperature, then there's a local minimum followed by behavior similar to that of thinner films[1] – resistance first grow, then reaches the maximum value, and, finally, decreases to zero.

We demonstrate that such features of *R(T)* dependencies of relatively thick films are due to transition from 3D-behaviour described by Bloch-Grüneisen formula to quasi2D-behaviour governed by the competition between weak localization, electron-electron interaction, and superconducting fluctuations.

We have found that current-voltage characteristics are strongly non-linear. At the lowest temperatures it is shown to be caused by depairing of vortex-antivortex pairs i.e. the BKT transition.

Focusing on the nonlinear conductivity above the superconducting critical temperature we show that the nonlinear transport in the temperature region where superconducting fluctuations dominate arises from an electron heating effect. The electron-phonon coupling constant in heat balance equation is shown to be almost constant for all films.

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High field termination of a Cooper-pair insulator

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Some highly disordered thin-film superconductors such as amorphous indium-oxide show a giant insulating peak induced by a magnetic field. Mounting evidence exists that this magnetoresistance peak is comprised of localized Cooper-Pairs which would imply a termination of the insulating state at the field when the Cooper-pairs are locally broken. To study the nature of this high-B state and the physics governing the transition into this state we conducted a systematic study of samples with varying degree of disorder spanning the range from clean superconductors, having no magnetoresistance peak, to highly disordered samples that are insulating at B=0. The result of this analysis is the evidence that in all disordered samples the high-B trailing edge of the magnetoresistance peak occurs at a field value that corresponds to Hc2 in our cleanest samples. This correlation indicates that the high-B state beyond the insulating peak is dominated by unpaired electrons.

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